TABLE 1.—*Mean monthly and annual air temperatures, precipitation, and length of fire season (days) for the period 1909–1919, northern Idaho and Montana*

Zonation	Station	Elevation	Mean air temperature (°F.)													Length of fire season		
			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Beginning	Ending	Days
		Feet																
Prairies of eastern Washington.	(1)	1,000–2,000	27.7	32.6	41.6	49.9	57.1	63.7	72.5	70.9	61.6	50.6	39.0	29.9	49.7	4/15	10/16	184
Western yellow-pine forest	(2)	2,000–2,500	27.2	31.0	37.7	46.1	53.1	60.3	66.8	66.7	57.4	44.5	36.7	30.3	46.4	5/4	10/2	150
Western white-pine forest	Murray	2,700	25.2	28.5	34.4	43.2	50.4	56.4	62.9	61.7	52.2	44.0	33.4	27.4	43.3	5/14	9/23	132
Western white-pine forest	Burke	4,080	22.0	26.4	32.3	38.6	44.8	51.4	59.9	58.2	53.2	43.2	33.0	22.4	40.4	6/8	9/23	107
Subalpine forest	Roosevelt	7,500	19.2	21.4	25.0	32.7	38.3	47.6	56.6	56.6	48.9	41.0	27.8	22.0	36.4	6/25	9/9	76
			Precipitation (inches)													July–Aug.		June–Sept
Prairies of eastern Washington.	(1)	1,000–2,000	1.30	1.25	0.76	0.55	1.04	0.76	0.31	0.45	0.48	0.83	1.54	1.42	10.69	0.76		2.00
Western yellow-pine forest	(2)	2,500	3.01	2.18	2.22	1.82	1.96	1.36	0.73	0.57	1.18	1.49	2.77	2.97	22.39	1.30		3.84
Western white-pine forest	Murray	2,700	4.72	3.62	3.34	2.13	3.27	2.72	1.38	1.37	2.31	2.75	5.71	4.40	37.72	2.75		7.78
Western white-pine forest	Burke	4,080	6.17	5.30	4.78	2.50	3.09	2.84	1.68	1.03	2.62	3.27	5.48	5.48	44.24	2.71		8.17
Subalpine forest	Roosevelt	7,500	2.81	3.01	3.92	1.40	2.03	2.33	1.48	0.82	0.94	1.12	2.46	3.80	26.02	2.30		5.57

1 Ritzville, Hatton, and Lind, Wash.
2 Spokane, Coeur d'Alene, and Potlatch, Idaho.

TABLE 2.—*Averages and extremes of weather conditions in August*

Forest zone or type	Place and elevation (feet)	Air temperature (° F.)			Relative humidity (per cent)			Wind movement (miles per hour)	
		Absolute maximum	Mean maximum	Mean minimum	Mean a. m.	Mean p. m.	Lowest monthly	Mean for month	Maximum monthly
Prairies of eastern Washington	Hatton, 1,100	112	88.8	49.2					
Western yellow-pine forest	Spokane, 1,943	105	82.3	53.6	64	25	16	5.3	6.5
Western white-pine forest, low station	Priest River, 2,380	101	81.6	41.8	65	39	24	2.7	6.0
Western white-pine forest, low station	Murray, 2,700	97	80.1	43.3					
Western white-pine forest, high station	Burke, 4,082	92	74.4	42.0					
Subalpine forest	Experiment station lookout, 6,000		68.6	51.0	60	46		8.9	
Subalpine forest	Monumental Buttes, 6,979		72.6	49.1		53	30	15.0	

A PRELIMINARY STUDY OF EFFECTIVE RAINFALL

By J. F. VOORHEES

[Weather Bureau, Knoxville, Tenn.]

SYNOPSIS

Since the water content of the soil does not change appreciably from year to year, each year's rainfall must escape in some manner.

In winter it escapes by evaporation and run-off in streams.

In summer it escapes by evaporation, by run-off, and by transpiration.

Transpiration may be increased at the expense of run-off by increasing the number and vigor of plants.

It appears that the possible effective rainfall for this region will average from 6 to 8 inches per year, which is enough to double the present average yield.

The above title was chosen because this paper is mainly an effort to analyse the problem and indicate the most promising line of attack; and because the data at hand were so general that we could hope to reach only general conclusions. It is believed that a more detailed study, using daily instead of monthly values, would throw much additional light on the subject.

Assuming that in any given region the water content of the soil does not change materially from year to year we are confronted with the fact that each year's rainfall disappears somewhere during the year. This is true whether there are plants present or not, and the object of this study is to learn what part of this water may be diverted for the use of plants. We shall attempt to make this determination by means of a comparison of total rainfall with run-off, supplemented by some data on leaching from the University of Tennessee Experiment Station, and by some data on evaporation from trees, obtained by the author.

It would seem that all of the rainfall can be accounted for in one of the following ways:

a. Evaporation from plant surfaces before reaching the ground.

b. Evaporation from the surface of the soil before penetrating to an appreciable depth.

c. Evaporation in the soil below the surface.

d. Surface drainage.

e. Subsurface drainage or leaching.

f. Transpiration.

Evaporation from plant surfaces.—A set of observations made by the writer under a cherry tree about 20 feet high and 18 feet in diameter showed that the bare tree with no leaves would prevent about 0.10 inch of water from reaching the ground during each rain. A rain gage was set under the tree and another about 25 feet away in the open. A collar was fitted around the trunk of the tree in the form of a trough with a spout, under which a tub was set. The tub was covered so that no direct rainfall or drippings from the tree could enter it.

The water that ran down the trunk of the tree and was caught in the tub plus the water caught in the rain gage under the tree always lacked about 0.10 inch of equaling the amount caught in the gage in the open. In the summer when the trees are in leaf the amount of precipitation failing to reach the ground would undoubtedly be greater.

When we come to farm crops the importance of loss may seem less evident, but since all the mechanism of plant surfaces is adapted for the elimination of water rather than for its absorption, and since it has been shown experimentally that plants will die if the roots are dry, no matter how wet the stem and leaves may be kept, it seems probable that at least as much would be lost here as was lost under the leafless tree.

Evaporation from the surface of the soil before soaking in.—It is the opinion of a number of men who have been consulted that a rainfall of 0.10 inch will practically always evaporate without penetrating the ground appreciably. If this is true it would seem permissible to assume that an equal amount is lost from each heavier rain. Evaporation from these sources will amount to an inch or more of rain per month for the winter months, and in the summer months this evaporation, supplemented by the *evaporation within the soil* will certainly not be less, and will probably be much greater.

Surface drainage.—Water lost by this method has never been measured by itself as far as the writer knows, but is included in the run-off of the streams, which has been measured.

Loss of water by subsurface drainage.—This may also be assumed to be included in the run-off of streams, with the possible exception of a portion that may reach the river at a point below where the flow of the river was measured.

As a check on this point, data obtained in a lysimeter experiment at the University of Tennessee Experiment Station were used. The data used were obtained from four iron cans one five-thousandth of an acre in area and 6 feet deep. Three were filled with soil, 5½ feet of subsoil and one-half foot of top soil, all well packed. The fourth can, used as a check on the rainfall, was empty. All were set nearly flush with the ground and so arranged that leachings would drain into receptacles in a near-by pit. The cans were set up in March, 1916, but as we had no run-off data for 1917 and 1918 the years 1919 to 1922 were used in this comparison. It would seem that in that length of time the soil in the cans would have reached an approximately normal condition. As there was no surface drainage, the leachings should equal leaching plus surface drainage in the field, and this should equal the run-off in the river unless an appreciable amount had escaped from the watershed through underground channels. The percentage of leaching for the cans and of run-off for the watershed for four years was as follows:

Year	Run-off	Leaching	Difference
	Per cent	*Per cent*	*Per cent*
1919	43	54	9
1920	41	47	6
1921	43	43	0
1922	45	45	0

Apparently the soil in the cans was not fully stabilized until after 1920, but it seems fair to assume from these results that a negligible amount of water escapes from the watershed underground.

We may now combine some of the ways in which water escapes from a region so that we have two methods in winter and three in the summer: In winter, evaporation and stream run-off; and in summer, evaporation, run-off, and transpiration. Now, since the amount of water lost by evaporation can not conceivably have any great effect upon transpiration, it is evident that as transpiration increases run-off will decrease.

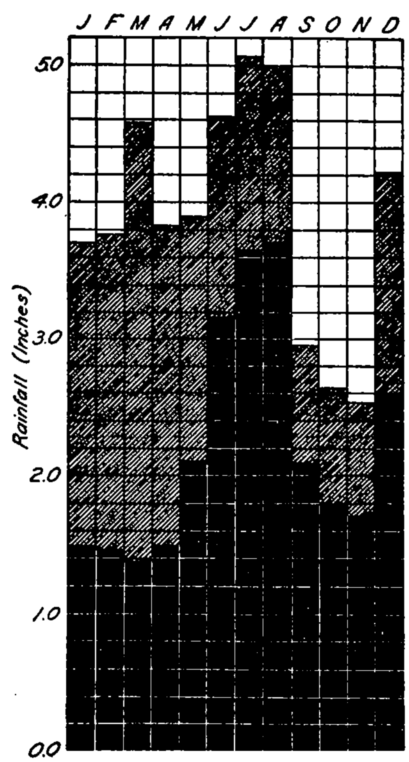

FIG. 1.—Monthly means of total rainfall and run-off, Knoxville, Tenn. Height of column shows total rainfall, upper shaded portion the run-off, lower black portion the remainder lost by evaporation or used by plants

We are now ready to consider our principal lines of data which are total rainfall and run-off. The run-off data were furnished by Mr. Warren R. King, of the hydrographic office at Chattanooga, and consist of the monthly run-off of the Tennessee River at Knoxville in inches for the drainage area of 8,990 square miles. These data cover the period 1900 to 1922, inclusive, excepting the years 1917 and 1918.

The rainfall data were computed from the published records of the Weather Bureau and include all stations in this drainage area. During the earlier years there were only 10 stations, but the number gradually increased until there were 20 for the later years of the series.

Fig. 1 shows the monthly means for total rainfall and run-off for the entire period of 21 years. The upper shaded portion represents the run-off, while the lower black portion represents the remainder of the rainfall which is lost by evaporation or used by plants.

TABLE 1.—*Monthly rainfall and run-off, in inches, at Knoxville, Tenn.*

Year	January		February		March		April		May		June		July		August		September		October		November		December		Annual		
	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Difference
1900	2.41	1.15	5.19	2.12	4.45	3.62	3.22	1.89	2.07	1.05	6.28	1.62	4.11	1.27	2.93	0.71	3.06	.65	2.22	.88	4.00	1.24	3.28	1.40	43.22	17.60	25.62
1901	3.98	2.24	1.25	1.44	4.78	2.10	5.36	4.63	6.62	4.17	5.13	2.83	2.96	1.51	12.52	4.38	3.03	1.92	1.77	1.10	1.02	0.67	9.68	4.17	58.06	31.66	26.40
1902	2.82	3.00	5.52	2.81	4.75	5.86	1.89	2.43	2.17	1.38	6.68	1.36	2.68	1.28	2.69	.66	4.86	.66	2.10	.64	2.86	.68	3.06	1.24	42.08	22.00	20.08
1903	2.18	1.30	7.38	3.58	4.71	4.95	6.12	5.22	2.26	1.53	4.21	1.65	4.19	1.02	4.05	.82	.91	.41	1.92	.34	3.17	.53	1.71	.49	45.31	21.84	23.47
1904	2.26	.72	3.26	1.15	5.43	2.85	2.54	1.32	2.90	1.36	3.85	.83	3.32	.77	3.84	.83	1.50	.41	0.07	.25	3.27	.36	3.45	.83	35.69	11.68	24.01
1905	3.17	1.60	4.40	2.68	2.64	2.09	3.53	1.58	5.48	2.33	4.02	1.15	6.38	2.03	6.16	1.86	1.29	.73	3.17	.56	0.84	.43	5.51	1.65	46.59	18.69	27.90
1906	5.78	3.12	1.08	1.59	4.25	2.10	2.60	2.05	3.52	1.58	5.72	1.51	7.07	1.67	5.38	2.27	4.52	2.56	2.82	2.51	3.76	2.48	3.74	1.96	50.24	25.40	24.84
1907	.95	1.86	2.46	1.34	3.52	2.44	3.83	2.03	3.54	1.75	3.58	2.76	4.13	1.44	3.57	1.05	6.25	1.29	1.52	.78	4.97	1.55	4.14	1.72	44.46	20.01	24.45
1908	4.27	2.26	3.60	2.72	4.22	3.33	4.36	2.52	4.06	1.78	3.35	1.25	5.50	1.23	5.87	1.35	1.80	.68	5.66	1.08	2.05	1.14	5.64	2.41	50.38	22.75	27.63
1909	7.76	2.10	4.85	2.88	5.95	3.98	3.79	1.91	5.70	3.01	7.56	2.79	5.36	1.97	4.20	1.36	3.26	.80	2.77	.70	0.56	.45	2.83	.68	49.54	22.63	26.91
1910	3.38	1.23	3.17	1.31	1.15	1.29	3.02	.77	5.10	1.30	4.32	1.22	6.62	1.59	5.72	.96	3.72	1.44	2.14	.61	1.30	.38	3.54	1.05	43.18	13.15	30.03
1911	3.81	1.91	3.40	2.31	4.62	2.21	6.05	3.30	1.46	1.26	2.68	.62	3.82	.62	4.29	.43	2.70	.49	4.53	.80	3.42	.80	2.66	1.20	44.44	16.15	28.29
1912	2.48	1.23	3.32	1.86	5.92	3.68	6.30	3.68	4.44	2.26	4.64	.99	5.72	1.38	4.01	.84	3.78	.62	1.65	.52	1.95	.51	3.06	.63	46.27	18.00	28.27
1913	5.24	2.42	3.75	1.66	7.10	4.54	2.85	1.90	5.75	2.03	3.44	1.30	2.81	.64	3.49	.59	4.10	.51	2.54	.52	1.52	.51	2.64	.59	45.23	17.21	28.02
1914	1.95	.74	3.35	1.31	4.21	1.65	3.94	2.29	1.37	.86	3.23	.57	5.09	.52	4.86	.59	1.76	.39	4.05	.82	2.70	.47	7.35	3.00	43.86	13.21	30.65
1915	3.96	2.77	3.55	2.31	2.40	1.19	1.46	.89	5.65	1.05	4.80	1.03	4.64	1.29	5.16	.77	3.37	.79	2.89	1.02	3.29	.82	5.95	2.65	47.12	16.58	30.54
1916	4.37	3.61	4.39	2.70	3.11	2.25	2.22	1.42	3.84	.90	4.63	1.05	10.89	4.06	4.85	1.80	2.20	.64	2.47	.60	1.96	.49	3.01	1.03	47.94	20.55	27.39
1919	4.98	3.64	2.90	1.96	3.64	2.65	3.22	1.55	4.98	2.13	5.27	1.41	3.48	1.15	3.82	.85	1.20	.45	4.77	.81	1.58	.56	3.62	1.83	43.46	18.99	24.47
1920	3.52	1.78	3.51	2.01	5.95	3.75	6.07	4.05	2.43	1.27	5.34	1.34	4.68	1.03	8.73	2.25	4.23	1.45	0.63	.67	3.60	.86	5.15	2.50	54.04	22.96	31.08
1921	3.86	2.25	4.28	3.43	2.59	1.61	3.85	1.92	3.84	2.01	3.96	1.13	6.72	1.60	5.37	1.95	2.81	.76	2.46	.56	3.77	1.02	2.43	1.45	45.94	19.66	26.28
1922	4.72	2.94	4.11	2.67	7.00	4.22	4.50	2.66	4.52	2.82	4.12	1.44	6.26	1.71	3.34	.89	1.43	.55	2.67	.52	1.22	.40	6.92	2.19	50.81	23.00	27.81
Means	3.70	2.19	3.76	2.29	4.57	3.20	3.84	2.34	3.90	1.79	4.61	1.42	5.07	1.40	4.98	1.27	2.94	0.85	2.61	0.81	2.52	0.81	4.25	1.66	46.55	20.03	26.52
Difference	1.51	-----	1.47	-----	1.27	-----	1.50	-----	2.11	-----	3.19	-----	3.67	-----	3.71	-----	2.09	-----	1.80	-----	1.71	-----	2.59	-----	-----	-----	-----

In considering this figure it must be remembered that while the shaded portion shows the actual run-off for each month at the gaging station, it does not show accurately the part of each month's rainfall that ran off, because a part of the run-off from one month's rain does not reach Knoxville until some time in the next month. A study of the table will reveal a number of instances when the rains of one month showed in the run-off of the next. Without daily values it has not seemed practicable to determine the exact amount of this shift. As a matter of fact the shift itself is often modified by the character of the rainfall. Five inches of rain falling at an excessive rate between the 20th and 25th of any month would mainly pass Knoxville in that month, as there would be a high percentage of surface drainage; but the same amount spread evenly over the same five days would not arrive until the month following, and in winter might even be as much as two months late.

Turning again to our figure and remembering our conclusion that the winter rainfall disappeared either in the run-off or by evaporation, we find that the amount evaporated during the first four months of the year, or before there is any appreciable plant growth, is approximately 1.5 inch per month, or a little more than was calculated from other considerations. For the next four months the run-off rapidly decreases while the rainfall increases just as rapidly. This decreasing run-off under such circumstances must be due to one or both of two causes—transpiration and increased evaporation.

During the fall months the rainfall and the run-off both decrease about 40 per cent, while evaporation probably remains a little above the winter average and transpiration becomes very small.

December, the first wet month following a series of dry months, shows some peculiar characteristics. Although transpiration has practically ceased and evaporation might be expected to show more of the winter characteristics, there is a marked increase in the amount of water that does not appear in the river. There are two reasons why this indicated increase is more apparent than real. First, the amount of run-off carried over from December to January is undoubtedly much greater than the amount brought from November into December. Second, the abnormally dry condition of the fall, with its failing springs and drying wells, is being changed to the normal winter condition of saturation. This probably requires a large part of the extra inch of rainfall that does not appear in the run-off.

Under present farm methods the average crop uses from 3 to 4 inches of rainfall. The run-off during the period of active transpiration of any crop will average from 4 to 6 inches, and if the crop is to be increased it must capture a part of that run-off. This can not be done by the mechanical prevention of surface drainage, because that would only increase the amount leaching through, as was shown in the lysimeter experiment explained above. It was also found in this experiment that all leaching occurred within 48 hours after the rain ended.

Apparently, then, the only way to make use of a part of this surplus rainfall is to increase the quantity of roots in the soil. This increased root growth will get more water in two ways. It will catch some in transit, as it were, before it gets out of reach, and it will reduce the water content of the soil to a lower level between rains, thus requiring more to saturate it again when the next rain comes. This process involves the danger that if rains come too far apart the crop may suffer.

Since it is not likely that it will ever be possible to utilize all of the present run-off, and since this run-off averages only from 4 to 6 inches during the active transpiration season of most crops, it appears that we can not hope to more than double the average yield in this section. This conclusion agrees with the experience of the University of Tennessee Experiment Station, where it has been found that about twice the average yield for the region seems to be their limit for production.